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Design Principles for Prototype and Production Magnetic Measurements of Superconducting Magnets*

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DESIGN PRINCIPLES FOR PROTOTYPE AND PRODUCTION

MAGNETIC MEASUREMENTS OF SUPERCONDUCTING MAGNETS

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ABSTRACT:

The magnetic field strength and shape for SSC superconducting magnets will determine critical properties of the accelerator systems. This paper will enumerate the relations between magnetic field properties and magnet material selection and assembly techniques. Magnitudes of various field errors will be explored along with operating parameters which can affect them. Magnetic field quality requirements will be compared to available measuring techniques and the relation between magnetic field measurements and other quality control efforts will be discussed. This will provide a framework for designing a complete magnet measurement plan for the SSC project.

INTRODUCTION

The quality control measurement[1] of superconducting accelerator magnets[2] has several interesting aspects, of which some are unique to the accelerator problem and others are special to the superconducting magnet problem. This paper will attempt to define a strategy for viewing this problem and supply an overview of its engineering and management aspects. Specific results and analyses will be included to make the discussion as concrete as possible and to provide a reference for further work.

Superconducting magnets such as the dipoles[3,4] designed for the SSC[5] have been classified as ''coil dominated'' magnets.[6] The critical magnetic field properties are largely set by the current flowing through the coils and the coil geometry. Iron yokes which surround the coil create enhanced fields which can be described with an image current model at fields below iron saturation. A more detailed analysis is required at high fields to describe the iron effects after the onset of saturation. In addition to the dominant transport current fields, hysteretic fields due to magnetic materials (both ferromagnetic (yokes) and ferrimagnetic (superconducting cable)) are very important at low fields. Both eddy current and flux creep effects cause time dependences of magnet fields. To plan an effective magnetic testing program, an overview of these effects is necessary. Since various properties determine different field errors, techniques must be devised to separate these effects and relate measured properties to fabrication techniques and materials properties.

Table 1. Uses of Magnet Measurements

*Production Quality Control

Use	Typical Measurement
Assembly Tooling	Measurement of Field Angle
Acceptance Testing	Maximum Current (Strength) Strength vs Current Field Uniformity
Optimize Installation	Field Uniformity Field Strength vs Current

*Prototyping and Special Magnet Design Tests

*Special Tests for Accelerator Systems

In Table 1 are listed various uses for magnet measurements of accelerator magnets. Let us examine these purposes for measurements and some of the measurements themselves. Then we will begin examination of the design considerations for hardware and software to be used in magnet measurements.

As part of the process of magnet fabrication, some of the assembly steps are more easily carried out using ''magnetic tooling'' (magnetic measurements performed to allow critical alignments or adjustments).[7] Most such steps will be carried out with factory based measurement equipment. However, in the fabrication of the Fermilab Tevatron dipoles, in addition to the field angle determination during assembly, adjustments of the relative positions of the iron and coil during final testing allowed a significant improvement in field uniformity. Field angle measurements of dipole and quadrupole magnets provided alignment data for tunnel installation which substantially reduced the magnet assembly precision requirements.

Acceptance testing of the produced magnets will determine their suitability for use in the accelerator. Typically, measurements of the properties required (performance tests) are the preferred technique for acceptance testing. However, it may be possible in the case of superconducting magnets to provide cheaper or more sensitive tests in other ways. Total project cost may be reduced by performing specially designed tests to portions of the magnet during assembly. In addition, some tests may be desired which can reveal production line malfunction which will be corrected for ''good engineering practice'' since determining the true effects on the accelerator (material fatigue, long term insulation failure...) may be more expensive than correcting the manufacturing problem.[8] The result of acceptance testing will be accepted magnets, rejected magnets, and perhaps some magnets which will be repaired.

The 20 TeV synchrotron proposed for the SSC project will perform as a single tool. Thus, the product of the magnet builders is not a set of 10,000 magnets but instead is ONE machine. This distinction was important for the existing Fermilab Tevatron since the properties of the produced magnets would have produced an inferior accelerator if assembled with randomly chosen magnets from the assembly line. Instead, in a process referred to as ''shuffling'' but which could better have been called ''stacking the deck'', properties of sets of magnets were matched to provide improved accelerator properties.[9] Magnetic measurements were performed on each magnet to make this possible. More stringent magnet fabrication requirements or additional magnetic correction schemes would have been the (more expensive) alternatives. The usefulness of this requirement will be determined by the relationship between the accelerator design and the achievable tolerances on materials for and assembly of the magnets.

In addition to these production requirements, there will continue to be a series of measurements required which must be implemented as special tests. These prototype measurements will need to be carried out both to resolve any magnet design questions which arise but also to provide information about the magnets for the design of related systems such as power supply systems or quench protection systems. These will not only require different and additional resources, but may also need to be integrated into production measurements, either because of requirements to achieve sufficient statistics, because the measurement is closely related to existing measurements or simply to achieve the same high quality of data collection and management achieved by the production measurement system. This requirement for special tests along with the assurance that the initial set of production measurements will require small adjustments in order to achieve all project goals, demands a flexible measurement system implementation. Modern tools allow a well defined and well monitored production measurement system which is also flexible.

In order to accomplish the various tasks in Table 1 we will need a variety of magnet measuring tools and systems. Each system will require its own special considerations concerning

Implementation
Record Maintenance and Reporting
Measurement Quality Assurance

The importance of attempting to create a common set of tools for handling this diverse set of measurement requirements is driven by the need to minimize development costs and operating complexity. In addition, the complete understanding of a given set of measurement tools is challenging enough to suggest that the number of tools developed be minimized. After solving the problems for the 8000 dipoles, there will remain important measurements for main quadrupoles, correction packages, interaction region quadrupoles and the other special magnets required for the SSC main synchrotron. Measurements will also be required for the magnets in the injector accelerators. A well considered system rooted in well considered tools is critical to the success as well as minimizing the cost of this endeavor.

In this paper we will examine some of the measurements which have been developed or planned, explore the effects which control the desired properties but also place requirements on the techniques for measurement control, discuss the relation between magnetic measurement quality control tests and other available QC possibilities, and finally discuss various aspects of measurement design and data management design to allow this effort to be effectively managed and to integrate successfully with the overall requirements of the SSC accelerator project.

Table 2. Measurements Applied to Tevatron Superconducting Magnets

<u>Measurements under Cryogenic Conditions</u>

Measurements of Maximum Current Capability and Quench Protection

Ramp Quench	Linear Ramp to Quench
Cyclic Quench	Multiple Ramps to Each Target Current
Heater	Integrity of Quench Heater Circuits
	Full Energy Quench of Unprotected Magnet

High Current Magnetic Measurements

Harmonic Measurements of Field Quality
NMR Measurements of Dipole Uniformity
Integrated Field Strength and Field Angle Measurement

Miscellaneous Electrical and Low Current Tests

Hi Pot (electrical insulation test)
Field Angle with AC System
Field Angle from Monitor System (Yoke Coil)

<u>Measurements at Room Temperature</u>

Electrical Tests

Coil Inductance and Resistance
Hi Pot (electrical insulation test)

Magnetic Tests

Field angle with AC system
Field angle with Monitor System (Yoke Coil)
Field Uniformity (AC system)
Field Strength (AC system)

Mechanical Tests

Cryostat Position Measurements
Pipe Offsets
Yoke Shape

SOME TYPICAL MEASUREMENT TECHNIQUES

Let us briefly examine some of the measurements which are performed on superconducting accelerator magnets.[18] In Table 2 we have outlined the quality control tests done on the Fermilab Tevatron Magnets. Some were implemented to assure that the magnets met minimum requirements for the accelerator, some to check the operation of critical devices or to adjust some variable assembly feature and some recorded properties of assembled magnets to allow their optimal use in the accelerator.

In order to evaluate the maximum strength (maximum current) for a superconducting accelerator magnet, one may excite the coils with a prescribed excitation pattern and record the current at which the magnet is not able to sustain the superconducting state. When a portion of the coil ''quenches'' to the resistive state, the whole magnet will eventually become resistive. The measurement procedure must record the current and voltage development of this quench event in order to study the quench propagation, heat development and voltages created. These are typically measurements made to accuracies of 0.1% at best. Time resolutions of milliseconds are useful. A critical aspect of these measurements is the careful record of the cryogenic state of the magnet and the excitation history.

Measurements to determine the shape of the magnetic field have been carried out using rotating coils at fixed excitation currents. The results are expressed using a standard harmonic expansion of the magnetic field. By making use of sense coil configurations which were insensitive to the dominant (dipole or quadrupole) field, precise measurements (10^{-4} to 10^{-6} of the dominant) can be carried out with low precision electronics (12 bit ADC). Important limitations due to power supply constraints and probe motion imperfections can be avoided in this way also. The magnetic field shape will be sensitive to the magnetic history and cryogenic conditions of the magnet so these will be recorded by the measurement system. Measurements through all parts of the hysteresis cycle may be needed to assure proper materials selection and magnet assembly. The results of these measurements must be compared with the system requirements for the accelerator. Alternative techniques are under consideration including different rotating coil techniques, NMR arrays and arrays of Hall Probes are being examined but the considerations of this paper apply equally to all of the above.

The strength of the magnetic field can be recorded in various ways. The required information is the integrated strength along the centerline of the magnet. The dipole strength is $\int B\, dl$ whereas the quadrupole or sextupole strength is the integral of the relevant derivative of the field. Dipole strength has been successfully recorded using NMR probes for the body field in conjunction with Hall Effect Probes in the end fields where the field uniformity is not sufficient to observe the resonance for NMR. Stretched wire probes and rotating coils have been used for a variety of measurement systems to measure the integrated strength of both dipole, quadrupole and higher order correction systems. Required accuracies are typically 10^{-4} or better for dipoles with somewhat less accuracy required for quadrupoles. Again, the magnetic history will affect these measurements and must be carefully controlled to provide suitable results.

In addition to these ''generic'' measurement requirements, each magnet design will contain features which should be monitored and controlled. Often the magnetic measurement system will provide the most suitable technique for quality assurance. Such measurements will be integrated into the production measurement flow.

A MEASURERS MODEL OF A SUPERCONDUCTING MAGNET

Design tools exist to allow accelerator scientists to interact with magnet designers to provide a suitable design and manufacturing plan for creating superconducting magnets. However, the construction of a magnetic measurement system will profit from a model for the magnet which is more heuristic but more amenable to understanding the various effects. With such a model in hand, the results of measurements should be better understood, allowing a measurement plan to be developed which will reveal all interesting aspects of the measurements <u>and</u> the magnets. With such a plan in hand, the magnet measurement scientist in combination with the manufacturing engineer can plan a complete quality assurance system including mechanical measurements during fabrication and assembly (e.g. sizes and stresses), electrical measurements such as inductance and magnetic measurements of components and of the final assembly.

The nature of such a model is shown in Table 3. We can calculate the dominant effects with only the first two items since they dominate the field at all excitation levels. However, we notice that to determine them accurately, we will need to make measurements at intermediate fields so that other effects can be minimized. Our separation of the effects of the iron into three distinct contributions has not been convenient for magnet designer's codes. But the effects are very distinctive. The saturation effects turn on quite sharply in most conventional as well as superconducting magnets and can characterized quite distinctively at a limited range of (high) currents. Effects of mechanical deformation must be kept small in the design to avoid fatigue as well as to maintain suitable field quality. Separating such effects from ones due to iron saturation is difficult.

The fields created by the magnetization of both the iron and the superconductor[11] are most important at low fields. In fact, both are most easily studied by noting that they are nearly independent of field level (they create number of Gauss at a reference radius which changes less than a factor of two or three over the whole current range) When plotted as a fraction of the dominant field, they will, of course, fall quickly at high fields and are therefore of much less importance to the accelerator there. However, these effects depend critically on the magnetic history of the test magnet so this must be carefully recorded and controlled. In particular, for measurements at a fixed current, the current must approach the target current smoothly since small overshoot will product large changes in the hysteretic fields.

The effects of flux creep on the fields of accelerator magnets has only been appreciated recently.[12] This effect adds considerable difficulty to attempts to make precision measurements of magnetic fields since the observed effects appear to depend sensitively on the detailed magnetic history. Although the effects are fairly small, they have been observed to create important changes in the operation of the Fermilab Tevatron.[13] Although Table 3 lists them as being important at low

Table 3. Sources of Magnetic Field

Effect	Calc Tool	Range	Hysteresis	Temp. Effects
Current in Coil	Amperes Law	All Fields	none	No
Infinite μ Iron	Image Currents	All Fields	none	Small
Iron Saturation ($\mu < \infty$)	(requires detailed calc)	Hi Fields	???	Small
Iron Remanent Field	Magnetic Charges	Low Fields	YES	Small
Persistent Currents in Superconductor	Doublet Theory	Low Fields	YES	Yes
Mechanical Deformation	Finite Element Code + Ampere	High Fields	NO ??	No
Flux Creep in Superconductor	Low Fields	YES	Small	

fields, their effects at high field will depend on the details of the SSC accelerator design and the significance of such effects cannot be ruled out a priori. It is perhaps suitable to suggest that this effect be taken as representative of perhaps several important small effects which require that the magnet measurement system be designed with a comprehensive view to provide detailed measurements and flexible implementation so that new effects can be studied and then monitored as required.

By studying these effects in detail, on can obtain an understanding suitable to allow the design of the measurement system details and to prepare analysis systems which will provide the required monitoring of results so that both the quality of the magnets and the quality of the measurements can be assessed.

SOME CONSIDERATIONS OF MEASUREMENT SYSTEM HARDWARE

The measurement system will require a variety of tools. All will be familiar to the accelerator builder but the special tasks associated with the quality assurance aspect of the magnet measurement facility will require special attention to these features so that suitable systems can be chosen for this purpose. It is often advantageous to apply some of the systems which will be utilized in the accelerator complex to the magnet measurement problem in order to provide system testing experience for them. However, this must not get in the way of the principle purpose: quality magnet measurements. To illustrate this point, we will contrast in Table 4 typical power supply and current readout requirements for measurements and accelerators.

Table 4. POWER SUPPLY FEATURES

Feature	Magnet Meas. Req.	Accelerator Req.
Current Stability	0.0001 for 200 Sec.	.00002 for 20000 Sec.
Ripple	<0.3% Typical	<.005% Typical
Overshoot	<0.1 A Max.	0.1 A Reproducible
Ramp Rate	Variable (per meas.)	As specified
Setting Accuracy	<1% Typical	<0.005% Typical
Setting Precision	0.1 A Typical	0.01 A Typical
Readout Accuracy	<0.01%	<0.1% Typical
Control at Zero Current	Important	Irrelevant

A number of other hardware considerations will distinguish the high volume, precision Quality Assurance magnet measurement system from other familiar hardware systems. The significance of the measurement for the life of an accelerator makes it useful to tie the measurement to absolute references via calibration precedures. When industrial vendors are involved it is recognized that it then becomes commercially as well as technically useful to tie these calibrations to NBS standards. In order to assure that the hardware used for the measurement is well identified (so that its calibration is known), an electronic identification which can be read by the data collection system is needed. Simple systems suitable for existing measurement systems have been in use for some time at Fermilab. Systems which are suitable for expansion to a large scale effort need to be identified and implemented.

Magnetic field measurement techniques must be selected for which problems of calibration, data acquisition, analysis and monitoring are understood. However, the same concerns must be shown for control and readout systems for cryogenics, current, probe position and magnet orientation (as examples). ''In place'' calibration is desired. Redundant measurement allow the monitoring of stability and reliability to be carried out within the nominal data flow. The optomization criteria must take note that the cost of additional routine measurements carried out by the computer is very low, additional measurements performed routinely by the measurement personnel is still inexpensive but calibration and especially diagnostic work carried out by the scientific staff is very costly in both direct cost and opportunity cost.

DATA COLLECTION ENVIRONMENT

Implementation of the measurements required for the SSC project is clearly a project which deserves the use of modern computer software and hardware tools to make the implementation meet its goals and remain cost effective. An appropriate place to start consideration of these tools is the axiom which states that all computer applications need to be designed so that the people who use them find the computer to be their assistant rather than being made to feel that they are the computer's assistant. In each phase of the design one needs to focus on the person who is to be served by the process under design. The widest context which we will consider here is the accelerator scientist for whom the measurement data is obtained. The most restricted view is that of a technician who calibrates measurement equipment or a materials management clerk who maintains product and equipment inventory information. Table 5 lists some of the personnel involved in this process. Their domains of view are described with terms intended to be suggestive but not at this point analytical.

Table 5. Domains of Interest of Measurement System Users

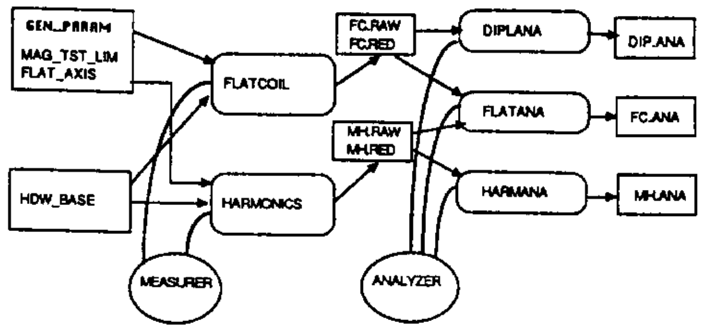
User	Domain of View
Accelerator Scientist	Measurement Analyzed Results (Production and Prototype) Inventory of Products
Measurement Scientist	Measurement Results Raw, Reduced and Analyzed Equipment Status
Measurement Manager	Measurement Status and Results Inventory of Products Equipment Status
Measurer	Equipment Status Local Product Inventory Measurement Results - Raw and Reduced
Data Analysis Clerk	Measurement Results - Reduced and Analyzed
Equipment Technician	Calibration System Status Equipment Status

The point of view adopted in the measurement system created for the AntiProton Source project[14] is that the principle design goal was to allow the Accelerator Scientist and the Measurement Scientist (engineers and physicists) to have full control of all information they required to evaluate the quality of the magnets and measurements by making it available through the computer system. This implied the need to provide databases to control the calibration information used in the measurements, configuration files to provide consistent information on equipment and settings, careful design of the results files to provide all the information which must flow through each step of the measurement process. It requires that the computer read all status information electronically to eliminate, where possible, errors due to operator data entry. (Experience at the Fermilab MTF indicates that error rates for entry of status information can at best approach 99% accuracy). This requires a degree of planning in both the hardware and software implementation so that the required ''near 100%'' status readout is possible.

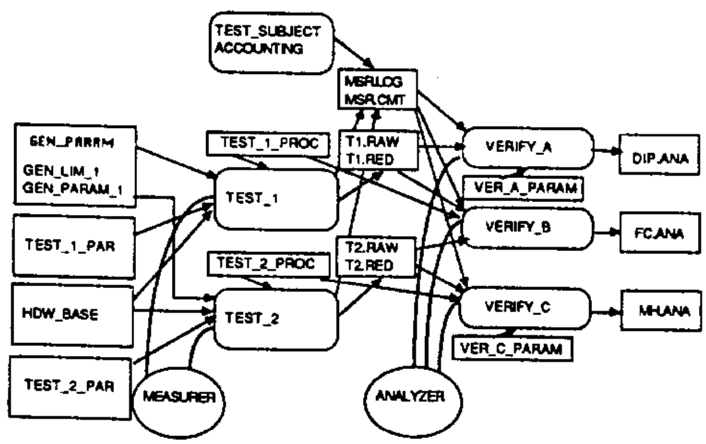
The programs were written as single threads of code which directed the measurement process from beginning to end. It was required that the data be recorded in both Raw form and Reduced form (calibrations applied) by the initial data collection program. The requirement to record the raw data is widely utilized in any application where data volume permits. This will allow a reprocessing of the data with updated calibration information or revised programs if that should be required. Data analysis may proceed in one or more passes to provide a variety of required results. All data was organized to allow use of data management tools (in this case DATATRIEVE)[15] for general data viewing and monitoring. Data management software has been written using both traditional and data management languages. The only data recorded outside of this procedure was operator commentary which was recorded in an electronic logbook.

The measurement system utilized for measurement of prototype SSC 17 m dipole magnets[16] at Fermilab has employed some significantly different styles than those used for the production measurements described above. In particular, the very much more extensive instrumentation requirements of this phase of measurement has been provided for using multitasking software. This has provided the ability to make measurements of the (cryogenic) environment of the magnet under test with separate code from the process which was directing the magnet test sequence.

Based on this experience, some of the deficiencies of these systems have been observed. The degree of automation available in the AntiProton Source system was limited by available hardware automation. In anticipation of systems with further automation in the hardware, a plan has been outlined and partly implemented which meets some of the problems inherent in the previous systems and to allow for a higher degree of automation in the data collection and data management. The AntiProton Source System was originally used for storage ring magnets which were intended to be used at a single current for which a prescription of a pre-ramp (hysteresis ramp) was sufficient. However, as this system has been used for accelerator magnets, the schemes available for recording the results at different portions of the excitation cycle have required ad hoc changes to the procedures and no integrated method to record hysteresis or current control information was available. Recently, an incremental addition has been implemented to provide a single record structure in which measurement history (programs requested, files written, measurements approved), current history and the electronic logbook can all be written to a single file which is still easily accessed with the existing data viewing tool (DATATRIEVE). The intention is to provide two classes of data output: status data which accumulates in a chronological log and run data which are written as records of prescribed structure to a separate file for raw and reduced results for each measurement type. It is believed that this structure MAY be sufficient for a fairly automatic measurement and analysis procedure based on command files. Figure 1 outlines the data flow of the previously mentioned system and a system which has now been partly implemented for a more automatic measurement system.



DATA FLOW DIAGRAM
EXISTING (SEMI-AUTOMATIC) TESTS



DATA FLOW DIAGRAM
PROPOSED (AUTOMATIC) TESTS

Figure 1. Plan for information flow in magnet measurement systems.

The criteria for deciding between further complexity of a given data recording structure and the complexity of adding additional structures requires some discussion. It is likely that the limitation of importance is the channel capacity and buffer capacity of the human perception process. A useful discussion can be found, for example, in Chapter 19 of James Martin's Design of Man-Computer Dialogs.[17] We learn there that for each level of abstraction, up to about seven items can be recalled and manipulated in our senses at one time. To extend the capacity to deal with complexity, we are advised to group materials in to manageable patterns which can then be manipulated further. This suggests that we are wise to select a limited number of files or databases and to provide modest levels of complexity in each.

Based on experience with existing measurement system and the programming effort required to produce them we can conclude that several classes of commercial software are likely to be interesting for constructing Quality Assurance Magnet Measurement Systems: Databases, Forms Management/Data Entry, Graphics, and perhaps statistical packages will be useful. Since the essence of automation is extensive software support of all aspects of the process, the volume of software will be substantial and will certainly justify investment is superior software development tools. It is ASSUMED that the hardware will be based on as many standardized items as possible. Commercial electronic hardware based on widely accepted IEEE or ANSI standards will certainly be the core for the data acquisition system. Mechanical hardware will require careful engineering since comparable national or international standards exist only at component, not system levels for mechanical hardware. The choice of standard (or at lease commercial) software is essential to the implementation of flexible, responsive and maintainable measurement software systems.

SUMMARY AND CONCLUSIONS

The tools required to implement measurement systems for SSC or other superconducting magnets are available. Although new measurement techniques may be considered as part of a new system design, the principles which are required for system planning can be enumerated now. The detailed plan for quality assurance of the component magnets of a superconducting ring must integrate quality assurance at all stages of the fabrication and acceptance of the materials and the magnets. The quality of the magnetic field will depend upon the materials and the assembly. The details of whether to spend more on testing of cable, insulation and laminations or on room temperature or cryogenic temperature testing of the magnets will depend upon the details of the magnet design. For example, the relative shape of the coil when warm or cold depends in detail on the system for coil support within the magnet. Support schemes have been proposed in which the coil is substantially deformed when warm in order to achieve sufficient support when cold. Such a design would suggest very different testing scenarios from those used for the Tevatron or HERA. Details of magnetization may be alternatively studied by detailed materials measurements or by measurements of the finished magnets. The principles which determine the sensitivity of various measurement options are outlined above.

The overall objective of the Quality Assurance project is to provide a reliable and well understood accelerator. To achieve this will certainly require magnetic measurements at many points. However, the requirement of a well understood accelerator which runs for long operating cycles with little down time can be acheived in different ways. With magnets whose manufacturing process guarantees magnets with precisions well beyond what is needed combined with some ''go/no-go'' type testing during or perhaps after the manufacturing process one can mimize the magnetic testing. Accelerator plus magnet designs are viable in which the manufacturing tolerances are much too tight to be achieved with large margins. For these designs, one will need more detailed testing.

The entire enterprise of assembling a large accelerator will require a data management structure which allows the Accelerator Scientist to have access to all the information he needs to monitor the progress of accelerator construction. A data flow plan for the measurement task has been outlined which is suitable for a measurement system with substantial automation. The measurement systems for SSC will grow along these lines in order to provide the quality measurement information required by the accelerator construction enterprise.

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This work is an exploration of the issues concerning quality assurance magnetic measurements. It represents accumulated experience of projects at Fermilab related to the SSC needs but not management policy of either Fermilab nor SSC management. I would like to express my thanks to my Fermilab colleagues with whom I have explored these ideas including John Carson, Gene Fisk, Moyses Kuchnir, Mike Lamm, Paul Mantsch, Peter Mazur, Rich Orr, John Peoples, Jim Strait, Frank Turkot, and especially Ray Hanft and Dave Harding. Special thanks are also due to the measurement and development staffs of the Fermilab Magnet Test Facility. Fermilab is operated by Universities Research Association, Inc., under contract with U.S. Department of Energy.

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